Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 132 (2015) 529 – 536

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

Analysis of the Mechanical Deformations of Boring Tools

S. Koleva[a], M. Enchev[a], T. Szecsi[b,*]

[a]*University of Rousse, Depratment of Manufacturing Engineering, 7000 Rousse, Bulgaria*
[b]*Dublin City University, School of Mechanical and Manufacturing Engineering, Dublin 9, Ireland*

Abstract

In this paper, the mechanical load of boring tools is investigated. Derived are the equations for defining the deformations caused by the radial and axial components of the cutting force. Also presented is a function for the total deformation of the tool. Conducted are experiments for defining the mechanical deformations of boring tools caused by the radial component of the cutting force. As a result of the experiments the share of the axial and radial components of the cutting force in the total deformation is defined.

Peer-review under responsibility of the Scientific Committee of MESIC 2015

Keywords: Boring tools; Mechanical Deformations; Volumetric Deformations; Contact Deformations.

1. Introduction

In order to increase the productivity of machining operations, in many cases, it is necessary to work at the limits of reliability of manufacturing processes. During machining of parts on CNC machine tools the strategy for maximum efficiency is realised by uniting two or more individual operations into one and if possible machining the whole part at one set-up using the original (rough) datum surfaces[1,2]. Lately, the emergence of efficient cut-off inserts makes the usage of bar stock (up to 60 mm in diameter) for machining many parts economically justified. It allows the elimination of individual cut-off operations and reduces the number of set-ups during machining.

In order to reduce technological downtime on CNC lathes, the stability of boring operations is investigated in this paper.

* Corresponding author. Tel.: +353-1-700-8300; fax: +353-1-700-5345.
E-mail address: szecsit@dcu.ie

Peer-review under responsibility of the Scientific Committee of MESIC 2015
doi:10.1016/j.proeng.2015.12.529

2. Methodology and Procedure

Stability of a mechanical system in the context of this paper is characterised by the ratio of the deformations resulted by the loads (forces) and is called pliability (measured in m/N or mm/N). The problem of stability during turning operations is mainly connected with the use of boring tools. Boring tools with indexable inserts can machine holes with a minimum diameter of 7 mm, whereas monolithic boring tools made from cemented carbide – down to about 0.3 mm in diameter [3-5]. The depth of bored holes is limited by the stability (strength) of the cutting tool and by the removal of chips from the hole. At a length-to-diameter ratio $\frac{L}{D} \leq 2$ of the tool the stability of the technological system is high and the maximum material removal rate can be achieved. At $2 \leq \frac{L}{D} \leq 4$, the production rate is still good and the surface quality characteristic to this manufacturing process is still achievable. At $\frac{L}{D} \geq 4$, production rate and surface quality start to degrade at a high rate and the process may induce vibrations.

For high quality process planning and for assuring reliability of the manufacturing processes it is necessary to define reliable values of the parameters affecting the manufacturing process and those of the process itself.

During the cutting operation, boring tools are considered as beams loaded at their free (cutting) end by the cutting forces at the dimension-forming point of the cutting edge (point *O* in Fig. 1(a)). For easier calculations, this point of action is re-located onto the axis of the cutting tool (point *O’* in Fig. 1(b)).

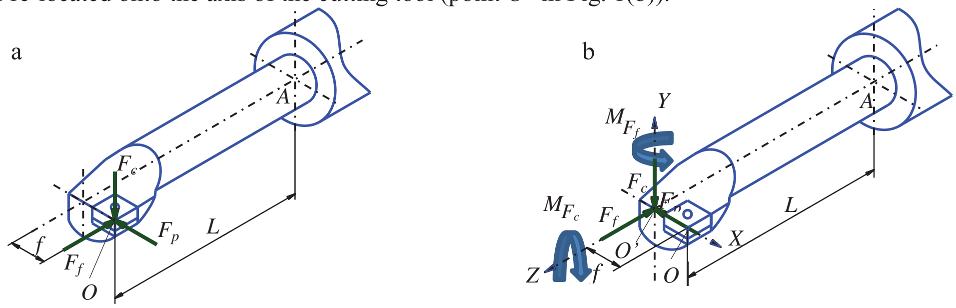

Fig. 1. Loading of a boring tool by the cutting forces.

As a result from the action of the radial cutting force F_p, the cutting tool is subjected to special cross bending. The moment M_{Ff} from the axial force F_f causes simple special bending, and the moment M_{Fc} from the force F_c – twisting. These forces and the resulting moments make the body of the tool deform, which is reflected on the accuracy of the machined dimension.

In many literature sources it is assumed that the mechanical deformations of the tool as a factor that influences the machining accuracy are the results of the volumetric deformations of the tool from the radial cutting force component F_p alone [3,4]. However, when working at the limits of the system, the forming of the deformations is also affected by the contact stability of the clamping devices the other cutting force components. The total deformation (displacement) of the tip of the tool in the direction of the dimension forming is the sum of the volumetric $\mathrm{y_v}$ and contact $\mathrm{y_c}$ deformations $\mathrm{y} = \mathrm{y_v} + \mathrm{y_c}$

2.1. Volumetric deformations

Volumetric deformations are induced as the result of the action of the force F_p and the torque M_{F_f}: $\mathrm{y_v} = \mathrm{y'_v} - \mathrm{y''_v}$

2.1.1. Volumetric deformations y'_v from F_p

Well known is the equation for defining the mechanical deformations of the technological system [1]:

$$y'_v = \frac{C_{F_p}(HB)^{z_{F_p}} h_{ver}^{w_{F_p}}}{j'_v + C_{F_p}(HB)^{z_{F_p}} h_{ver}^{w_{F_p}}} a_t \quad (1)$$

where the constant C_{F_p} designates the constant parameters at established cutting conditions and tool geometry, a_t – defined (theoretical) depth of cut, HB – hardness of the machined material, and j_v' is the volumetric stability of the tool. The expression $C_{\mathrm{F_p}}(HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}}$ in the denominator of the fraction has a much smaller value than j_v', so it can be neglected for easier calculations.

The cutting tool can be considered as a bended beam with length L, loaded at its free end by the passive component F_p of the cutting force. From [6], the dislocation of any point lying in the cross section, in which the force upon the tip of the tool is acting, can be expressed as:

$$y_v' = \frac{F_p L^3}{3EJ} = \frac{F_p}{\frac{3EJ}{L^3}} \tag{2}$$

Since in general terms: Deformation $= \frac{\text{Force}}{\text{Pliability}}$, the expression in the denominator represents the volumetric stability:

$$j_v' = \frac{3EJ}{L^3} = \frac{3E\pi d^4}{64L^3} = A\frac{D}{k^3} \tag{3}$$

where $k = L/D$, D – diameter of the cutting tool, $A = \frac{3E\pi}{64}$, E – modulus of elasticity, J – momentum of inertia.

After replacing the volumetric stability j_v' in the equation for the displacement y_v' we get:

$$y_v' = \frac{C_{F_p}(HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}}}{A\frac{D}{k^3}} a_t = \frac{C_{F_p}(HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}} k^3}{AD} a_t \tag{4}$$

2.1.2. Volumetric deformations y_v'' from the torque M_{F_f}

These deformations can be calculated as $\mathrm{M_{F_f}} = \mathrm{F_f f}$, where *f* is the distance of the dimension-defining point of the cutting tool from the axis of the tool (Fig. 1).

$$y_v'' = \frac{M_{F_f} L^2}{2EJ} = \frac{F_f f L^2}{2EJ} \text{ and } j_v'' = \frac{2EJ}{L^2} = \frac{2E\pi D^4}{64L^2} = B\frac{D^2}{k^2} \tag{5}$$

$$y_v'' = \frac{C_{F_f}(HB)^{z_{F_f}} h_{v_{er}}^{w_{F_f}}}{B\frac{D^2}{fk^2}} a_t = \frac{C_{F_f}(HB)^{z_{F_f}} h_{v_{er}}^{w_{F_f}} fk^2}{BD^2} a_t \tag{6}$$

2.2. Contact deformations

The sum of contact deformations is expressed as $\mathrm{y_c} = \mathrm{y_c'} - \mathrm{y_c''}$

2.2.1. Contact deformations y_c' from F_p

The contact deformations in the base surfaces of the cutting tool and toolholder device, resulting from the bending moment from the passive cutting force component F_p, can be expressed as:

$$M_{F_p} = F_p L = j_c \theta \tag{7}$$

where $j_c = M_c / \theta$ is the contact stability [3], θ – rotation of the tool under the influence of the bending moment, M_c – resistance moment from the contact deformations.

In order to express the dislocation of the tip of the tool, both sides of (7) are multiplied by L. After substituting in the equation of the passive force and the dislocation y_c' of the tip of the tool caused by the bending moment we get:

$$C_{F_p}(a_t - y_c')(HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}} L^2 = j_c y_c' \tag{8}$$

The dislocation of the tip of the tool is:

$$y_c' = \frac{C_{F_p} a_t (HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}} L^2}{j_c + C_{F_p}(HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}} L^2} \text{ and therefore } y_c' = \frac{C_{F_p}(HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}} L^2}{\frac{M_c}{\theta}} a_t \tag{9}$$

2.2.2. Contact deformations y_κ'' from the moment caused by F_f

These deformations can be calculated as:

$$M_{F_f} = F_f f = j_c \theta \tag{10}$$

$$C_{M_{F_f}}(a - y_c'')(HB)^{z_{F_f}} h_{v_{er}}^{w_{F_f}} f L = j_c y_c'' \tag{11}$$

$$y_c'' = \frac{C_{F_f}(HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}} f L}{\frac{M_c}{\theta}} a_t \tag{12}$$

After some rearrangement, the total deformation of the tool (volumetric and contact) in the direction of dimension forming is:

$$y = y_v + y_c = \left[C_{F_p}(HB)^{z_{F_p}} h_{v_{er}}^{w_{F_p}} \left(\frac{k^3}{AD} + \frac{L^2}{\frac{M_c}{\theta}} \right) - C_{F_f}(HB)^{z_{F_f}} h_{v_{er}}^{w_{F_f}} \left(\frac{fk^2}{Bd^2} + \frac{fL}{\frac{M_c}{\theta}} \right) \right] a_t \tag{13}$$

The sums in the brackets represent the volumetric ($w_{F_p,v}$ and $w_{F_f,v}$) and contact ($w_{F_p,c}$ and $w_{F_f,c}$) pliabilities of the tool corresponding to the radial and axial forces. There is no analytical equation for defining the contact pliabilities, so it is necessary to find a way to express them as part of the volumetric ones, for which we do have the equations.

The parameter f is expressed as a function of the diameter $f = mD$, and we find the ratio of the volumetric pliabilities:

$$q = \frac{w_{F_f,v}}{w_{F_p,v}} = \frac{\frac{fk^2}{Bd^2}}{\frac{k^3}{AD}} = \frac{\frac{1.5fk^2}{AD}}{\frac{Dk^3}{AD}} = \frac{1.5f}{dk} = \frac{1.5m}{k} \tag{14}$$

The equation $q = f(k)$ is shown graphically (Fig. 2) for three values of m. Data for m are obtained from catalogues of cutting tool manufacturing companies. In this case, the dimensions of boring tools with T-shaped inserts and with diameters of the boring bar 6 to 20mm are used.

It can be seen that the influence of m on the volumetric deformations is low. The intensity of the change of q decreases with the increase of k; at $k \geq 4$ the parameter q only varies in a narrow range of 0,3 to 0.18. Using q it is possible to define the percentage of the various pliabilities in the total one. In Fig. 3 this is shown for pliability $w_{F_f,v}$.

The decrease of the share of $w_{F_f,v}$ and the decrease of the share of $w_{F_p,v}$ can be explained by the fact that if the other parameters are fixed the influence of k is higher on the deformations caused by the radial force component compared to the ones caused by the moment from the axial force (see equation (13)). In the zone of insufficient stability ($k = 4 \div 6$) the axial cutting force component is responsible for 20% of the volumetric elastic deformations of the tool. Moreover, the positive influence of the moment from the axial force F_f on the resultant deformations of the tool decreases with the increase of k.

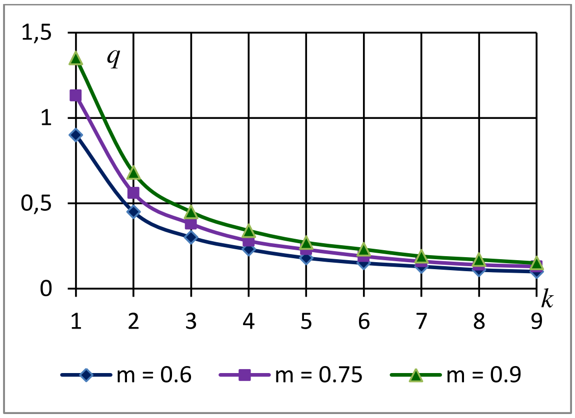

Fig. 2. Graph of the equation $q = f(k)$.

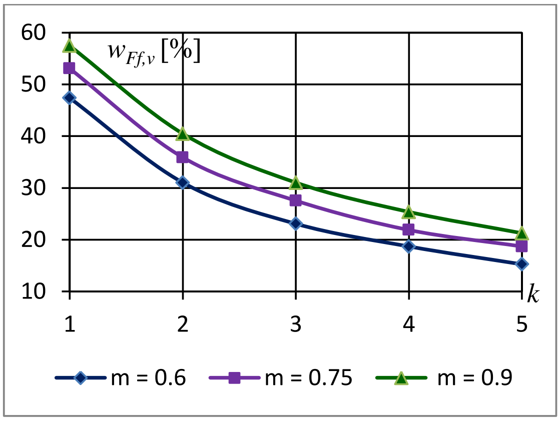

Fig. 3. Percentage of the volumetric pliability $w_{F_f,v}$.

For evaluating the pliabilities causing contact deformations under the influence of the radial cutting force F_p and the moment caused by the axial cutting force F_f can be found the equation:

$$p = \frac{w_{F_f,c}}{w_{F_p,c}} = \frac{\frac{fL}{\frac{M_c}{\theta}}}{\frac{L^2}{\frac{M_c}{\theta}}} = \frac{f}{L} = \frac{m}{k} \tag{15}$$

In Fig. 4, the equation $p = f(k)$ is shown graphically for three values of m.

Here the same considerations are in place as for q, but at $k \geq 4$ the value of p varies in the range of 0.15 - 0.1. As a result of this, the axial force component F_f is responsible for 15% of the contact deformations of the tool (Fig. 5).

These values of the shares of the deformations from the axial and radial cutting force components are defined under the condition that $F_f = F_p$.

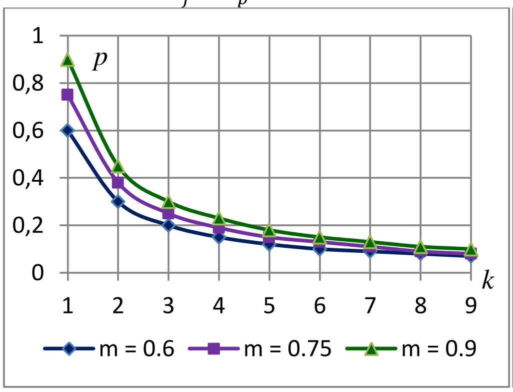

Fig. 4. Graph of the equation $p = f(k)$.

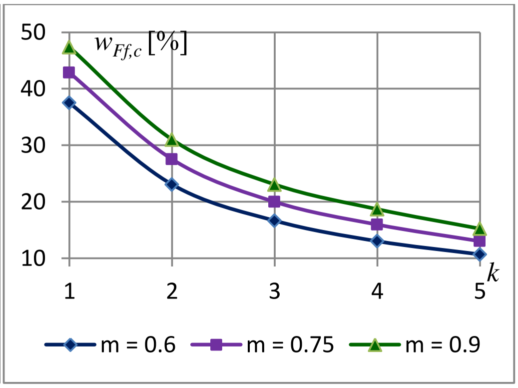

Fig. 5. Percentage of the contact pliability $w_{F_f,c}$.

Under the condition that the force components are not equal, the resultant deformation of the boring tool is calculated by:

$$y = F_p\left(w_{F_p,v} + w_{F_p,c}\right) - F_f\left(w_{F_f,v} + w_{F_f,c}\right) = F_p\left(w_{F_p,v} + w_{F_p,c}\right) - F_f\left(q w_{F_p,v} + p w_{F_p,c}\right) \tag{16}$$

In order to define the influence of the axial cutting force on the resultant deformation some rearrangements are made:

$$\frac{w_{F_{p,c}}}{w_{F_{p,v}}} = a, \qquad \frac{F_f}{F_p} = b \tag{17}$$

$$y = F_p\left(w_{F_{p,v}} + a w_{F_{p,v}}\right) - bF_p\left(q w_{F_{p,v}} + ap w_{F_{p,v}}\right) \tag{18}$$

$$y = F_p w_{F_{p,v}}[(1+a) - b(q+ap)] \tag{19}$$

The first part of the right hand side of (20) represents the share of the radial force, and the second part represents the share of the axial force in the resultant deformation of the tool. The ratio t/s is found, where:

$$(1+a) = s, \qquad b(q+ap) = t \qquad \Longrightarrow \qquad \frac{t}{s} = \frac{b(q+ap)}{(1+a)} \tag{20}$$

From the theoretical analysis for parameters q and p (Fig. 4 and 5) the following values can be found:

$$k = \frac{L}{D} = 3 \div 6 \rightarrow q = 0.45 \div 0.13\,; p = 0.3 \div 0.1 \tag{21}$$

For finding the value of the parameter $a = \frac{w_{F_{p,c}}}{w_{F_{p,v}}}$ representing the ratio of the contact and volumetric pliabilities from the radial force, additional research is necessary because an analytical equation for calculating the contact deformations does not exist. Because of this, their values have to be defined experimentally, and based on that the ratio $\frac{t}{s}$ can be found.

Performed are experimental studies for defining the actual deformations of boring tools caused by the radial force F_p. A boring tool with a free length equal or larger than the accepted ones from the viewpoint of stability during machining, that is at $k = 4$ and $k = 5$ was used. The experiments were performed on a CE063 CNC lathe, and the experimental equipment is shown in Fig. 6.

The boring tool 3 is fixed in the central position of the turret 8 using two bushings. Bushing 5 is made elastic (with a groove in it) and after the tool is positioned into it is clamped in the toolholder 7 using bolts 6. The rod 1 is clamped in the three jaw chuck 2. The load of the boring tool is measured by an electronic scale 9, the two ends of which are fixed to the rod and the tool, respectively. The force is applied in the direction of the passive force F_p which acts in the direction of the dimension forming. The force acting on the tool is measured by the calibrated scales, and the deformations of the boring tool – by a micrometric calliper 4 fixed to the body of the lathe.

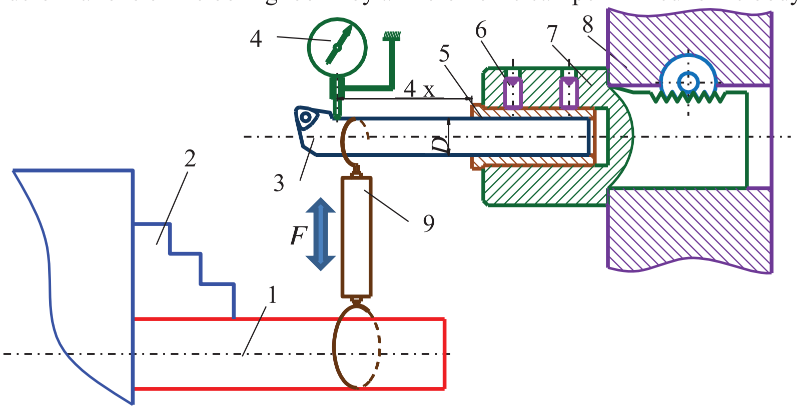

Fig. 6. Experimental equipment.

At this arrangement, the tool is considered to be a loaded beam. Its load and measurement of the deformations is performed at a distance equalling $4D$ measured from its fixed end, that is $k = 4$. Performed are experiments with loads from 10 to 100 N with a step of 10 N, with several repetitions. The results of the measured deformations y are averaged and are presented in Fig. 7 as a function of the loading force F. In the same figure is shown the theoretical equation of the deformation at the same conditions.

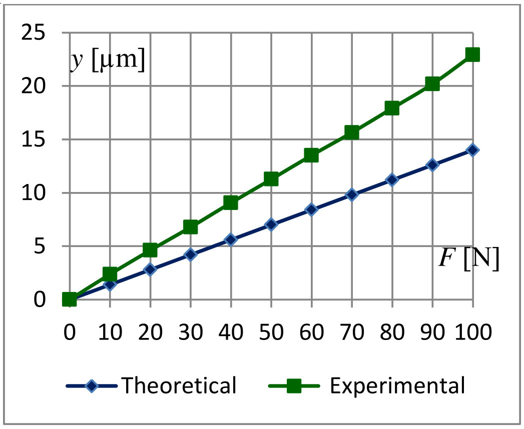

Fig. 7. Deformations of the tool with *Φ16 at k = 4*.

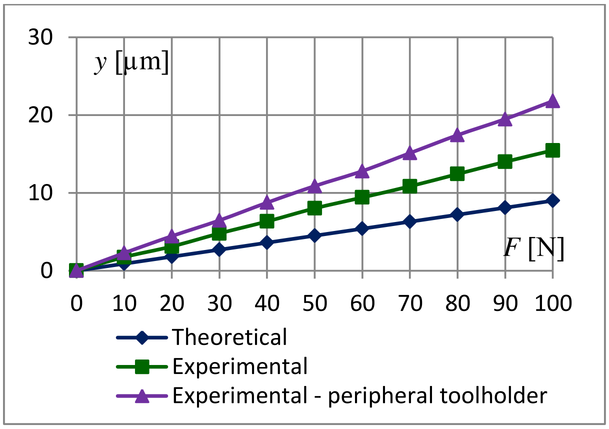

Fig. 8. Deformations of the tool using bushing with *Φ24 at k = 4*.

In order to eliminate the influence of the intermediate elastic bushing, an experiment is conducted, in which a boring tool with cross section Φ24 and free length $L/D = 4$ ($k = 4$) is clamped directly into the toolholder of the CE063 lathe. Also measured are the deformations when the tool is clamped into a peripheral position of the turret without the intermediate bushing or supporting plates. The loading scheme and measurement of deformations remained the same. The theoretical and experimental results of the measurements for both cases are presented in Fig. 8.

From the graphs it can be seen that the experimental results are different from the theoretical ones. The second one does not include contact deformations, occurring in the zone of contact between the tool and the turret, nor does it include the wear, damages and other defects of their base surfaces that would exist during actual machining. These unaccounted deformations in the theoretical calculations are contact deformations and their values can be found as the difference between the theoretical and measured volumetric deformations.

In Fig. 9 are given the shares of the volumetric and contact deformations in the resultant deformations measured at the corresponding applied force. The areas below the corresponding graph represent the share of the contact deformations, and the areas above the graphs – the volumetric deformations.

As a result of the experimental studies, for $k = 4$ and tool diameter Φ24 the ratio between the volumetric and contact deformations is $a = 0.7$.

Using the defined values of a, p, and q, one can find the ratio t/s representing the share of the axial and radial cutting force components in the resulting deformation of the cutting tool. Fig. 10 represents the function of this ratio $t/s = f(b)$.

During finishing operations, due to the recommended depths of cut [4-6], the actual cutting is performed by the nose of the tool with radius r_ε, or even with part of it. Therefore, it is not possible to obtain the higher range of b. Since in the reference sources it was not possible to find actual values of the cutting force components for finish boring, the exact value of b cannot be shown. On the basis of preliminary calculations it is expected that the ratio of the axial and radial cutting force components is in the range of $b = 0.4 \div 0.6$. In this case, the ratio of the pliabilities is $t/s = 0.09 \div 0.14$. In other words, the axial component has about 10% share in the resultant pliability of the cutting tool. The influence of a on the variation of the ratio of the pliabilities at constant b is negligible.

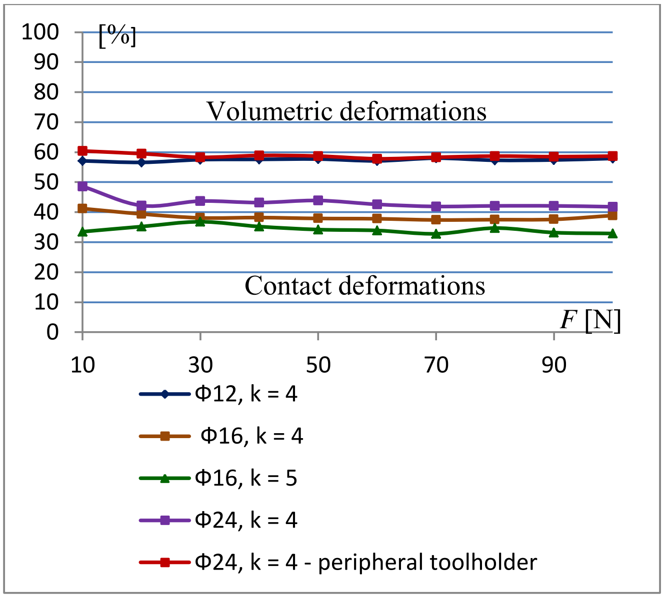

Fig. 9. Deformations of the tool with *Φ12 at k=4*.

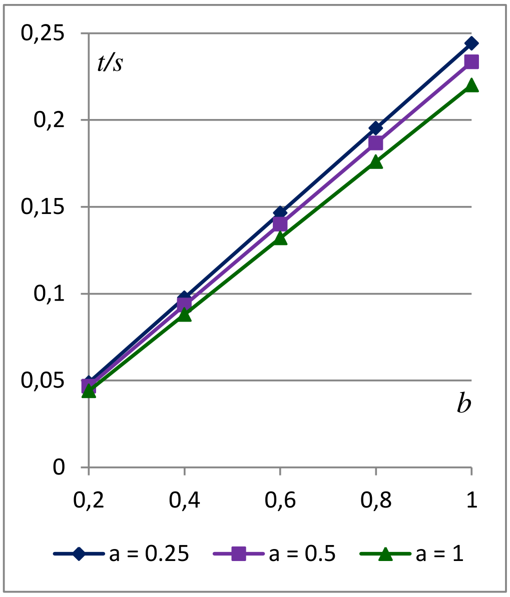

Fig. 10. *Graph of the function* $\frac{t}{s} = f(b)$.

3. Conclusions

The total deformation of a boring tool in the direction of dimension-forming is caused by the counter action of the axial F_f and radial F_p components of the cutting force which induce both volumetric and contact deformations.

With the increase of the free length of the cutting tool the influence of the axial force F_f on the volumetric and contact deformations decreases while the influence of the radial force F_p increases.

The axial cutting force component F_f at the ratio L/d 3÷6 has a low share (around 10%) in the deformations of the cutting tool; based on the experimental studies for defining the actual values of the radial cutting force component it can be accepted that the deformations of the cutting tool are the result mostly of the axial cutting force component F_p.

The contact deformations, measured at real (manufacturing) conditions of the mounting datum surfaces of the technological equipment have a 35%-60% share in the resulting deformations.

Under the same loading conditions, a cutting tool which is installed in the peripheral toolholder of the turret has a higher contact deformation than a tool installed in the central (cylindrical) toolholder pocket. This is the result of the difference in their datum schemes.

It is necessary to conduct more experimental studies for defining the value and scatter of the radial cutting force component at finish boring by measuring the deformations of the tool during the actual machining operation.

The results for the deformations of the boring tool can also be used in cases when a workpiece with low stability is being machined.

References

[1] I. Zamfirov, M. Enchev, G. Nenov, Manufacturing Technologies - Part 1: Foundations of Manufacturing Technologies, second ed., University of Rousse, Rousse, 2006.
[2] I.L. Fadjushin, Cutting Tools for CNC Machine Tools and Flexible Manufacturing Systems, Mashinostroenie, Moscow, 2006.
[3] ISCAR Catalogue – Turning Tools, 2014.
[4] SANDVICK Catalogue – Turning Tools, 2014.
[5] WALTER Catalogue – Cutting Tools, 2014.
[6] I. Kisiov, Tables of Mechanics of Materials, fourth ed., DI Technika, Moscow, 1985.